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Hazard Calculations of Diffuse Reflected Laser Radiation for the SELENE Program

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Abstract

The hazards from diffuse laser light reflections off water clouds, ice clouds, and fog and from possible specular reflections off ice clouds were assessed with the American National Standards (ANSI Z136.1 1986) for the free-electron-laser parameters under consideration for the Segmented Efficient Laser Emission for Non-Nuclear Electricity (SELENE) Program. Diffuse laser reflection hazards exist for water cloud surfaces less than 722 m in altitude and ice cloud surfaces less than 850 m in altitude. Specular reflections from ice crystals in cirrus clouds are not probable; however, any specular reflection is a hazard to ground observers. The hazard to the laser operators and any ground observers during heavy fog conditions is of such significant magnitude that the laser should not be operated in fog.

Introduction

Outdoor laser systems require two additional safety concerns not associated with indoor laser systems: (1) atmospheric scattering and (2) safe-viewing distances for specular and diffuse reflections for both laser operators and ground observers. Before an outdoor laser is operated, laser hazard levels are calculated and intensity levels are measured to help establish safety procedures. Outdoor lasers have been successfully used by the military services with the use of class 3 and class 4 systems in their laser range finders, laser target designators, and direct fire simulators. Only one laser injury occurred with these outdoor systems during the 1980's (ref. 1).

In addition, LIDAR (light detecting and ranging) has been used successfully since the early 1960's to remotely study the atmosphere (ref. 2). Initially, ruby lasers were used to analyze species and impurity concentrations of the atmosphere to distances up to 35 km. Now, gigawatt Nd:YAG lasers are being used to analyze impurities to distances of 100 km. Experiments measuring atmospheric pollution are performed at night to detect return photons because the signal-to-noise ratio is too small during the day. The concern that LIDAR reflections from clouds were a safety hazard generated many cloud models and reflection experiments.

The two types of reflected laser radiation are specular and diffuse (ref. 3). When the beam front remains intact and is as much a hazard as the primary laser beam, the reflection is specular. When the beam is reflected and scattered uniformly in all directions, the reflection is diffuse. Most reflections from clouds and haze are considered diffuse. This paper addresses the hazards of possible specular reflections from ice-forming cirrus clouds and diffuse reflected laser radiation from water clouds, ice clouds, and fog for the Segmented Efficient Laser Emission for Non-Nuclear Electricity (SELENE) Program.

Symbols

a	beam diameter, cm
H	radiant exposure, surface density of radiant energy received, J-cm^{-2}
H_o	emergent beam radiant exposure at range r, J-cm^{-2}
MPE	maximum permissible exposure, level of laser radiation to which a person can be exposed without hazardous effect or biological changes in eye or skin, J-cm^{-2}
$\mathrm{MPE_{DIFF}}$	maximum permissible exposure for diffuse reflected laser radiation, J-cm^{-2}
$\mathrm{MPE_{DIR}}$	maximum permissible exposure for direct ocular intrabeam viewing of a laser, J-cm^{-2}
NHZ	nominal hazard zone
n	number of pulses
prf	pulse-repetition frequency, Hz
Q	energy per pulse of a pulsed laser, J
r	distance, cm
r_{NHZ}	distance within which level of direct reflected or scattered radiation during normal operation exceeds MPE, cm
T	duration of exposure, sec
t	pulse duration, sec
θ_v	viewing angle, angle formed at target between laser beam and light reflected to human eye, deg
λ	wavelength, nm

μ	attenuation, decrease in radiant flux as it passed through an absorbing or scattering medium, cm^{-1}
ρ_λ	reflectivity of light at wavelength λ of a target
ϕ	divergence of laser beam, mrad

Computations

SELENE is a strategy for powering a lunar base (or an electric propulsion system) with laser power from the Earth's surface. In full operation, SELENE would consist of three ground-based stations equally distributed about the Earth to provide continuous direct power to the Moon. Each station would consist of an induction free-electron laser and a beam transmitter with a diameter of 10 m. Up to 10 MW of power at a wavelength of 0.8 μm would be transmitted through the atmosphere with the aid of a revolutionary optical telescope for projecting and correcting the beam. The Phase Array Mirror Extendable Large Aperture (PAMELA), a proprietary design by Kaman Corporation, is the conceptualized approach for this telescope.

The following approach for SELENE and PAMELA was discussed during the February 1991 Technology Workshop on Laser Beamed Power held at NASA Lewis Research Center. At the Moon, the beam would be received over an area of 80 m in diameter. Approximately 40 percent of the transmitted laser power would be received at the photovoltaic arrays on the Moon with a conversion-to-electricity efficiency rate of 50 percent. The parameters for SELENE are listed in table 1.

Table 1. Laser Characteristics for SELENE

Laser	Free electron
Wavelength, λ, μm	0.800
Pulse duration, t, nsec	10
Pulse repetition frequency, prf, Hz	10 000
Energy, Q, J/pulse	1000
Beam diameter, a, cm	10 000
Beam divergence, ϕ, mrad	1.84×10^{-4}

The maximum permissible exposure (MPE) for direct ocular viewing for a pulsed laser with a wavelength of 0.8 μm is determined by the following equation (ref. 4):

$$\mathrm{MPE_{DIR}} = 5C_A \times 10^{-7}\ \mathrm{J\text{-}cm^{-2}} \qquad (1)$$

where

$$C_A = 10^{2(\lambda-0.700)}$$

For SELENE, the MPE is 7.9×10^{-7}J-cm^{-2} for a single pulse. With a repetition rate as high as SELENE, the probability of a multiple-pulse exposure must be considered, and because the effects of pulses separated by several msec appear to be additive, the MPE for direct ocular viewing of multiple pulses is reduced by the factor $n^{-1/4}$ where $n = \mathrm{prf} \times T$. When used for this calculation, T is the duration of exposure but is limited to ≤ 10 sec (ref. 4). The corrected MPE for multiple pulses from SELENE is 4.4×10^{-8} J-cm^{-2}.

Because the optical telescope PAMELA corrects the beam, beam divergence is minimized. Without beam divergence, no safe distance exists for direct ocular viewing of the beam. Any exposure to the beam is above the MPE and is thus a hazard.

Even with PAMELA, some beam divergence will occur. Based on the parameters given, the calculated beam divergence ϕ is 1.84×10^{-4} mrad. When this parameter is included in the distance equation for direct ocular viewing of the beam, the safe-viewing distance is 9×10^6 km or $\approx 1/17$ of the distance from the Earth to the Sun. Nevertheless, any direct exposure is above the MPE for eyes and skin.

The MPE for viewing a diffuse reflection or an extended-source laser in the near infrared region is given by the following equation:

$$\mathrm{MPE_{DIFF}} = 10C_A t^{1/3}\ \frac{\mathrm{J\text{-}cm^{-2}}}{\mathrm{sr}} \qquad (2)$$

where

$$C_A = 10^{2(\lambda-0.700)}$$

for a laser with λ between 0.700 and 1.050 μm and a pulse duration between 10^{-9} to 10 sec (ref. 4). With the given parameters for SELENE, the MPE for diffuse viewing is 0.036 $\frac{\mathrm{J\text{-}cm^{-2}}}{\mathrm{sr}}$.

However, the hazard is better understood when the formula for the minimum safe-viewing distance for a diffuse target is used. For a pulsed laser, this equation is

$$r_{\mathrm{NHZ}} = \sqrt{\frac{\rho_\lambda Q \cos\theta_v}{\pi \mathrm{MPE_{DIR}}}} \qquad (3)$$

where ρ_λ is the spectral reflectance of a diffuse object at wavelength λ, Q is the energy per pulse, θ_v is the viewing angle, and the MPE is for direct ocular viewing (ref. 4).

For a worst-case scenario, a 100-percent-diffuse-reflective surface ($\rho_\lambda = 1.0$) and a viewing angle close to 0° ($\cos\theta_v = 1$), the minimum safe distance from the reflective surface is 850 m. In other

Table 2. Parameters and Laser Hazards for SELENE and Typical Laboratory Pulsed Laser

Parameter	Laser	
	SELENE (free electron)	Q-switched Nd:YAG
Wavelength, λ, μm	0.8	1.06
Pulse duration, t, nsec	10	15
Pulse repetition frequency, prf, Hz	10000	10
Energy, Q, J	1000	150×10^{-3}
Beam diameter, a, cm	10000	2×10^{-2}
Beam divergence, ϕ, mrad	1.84×10^{-4}	0.2
Peak pulse power, W	10^{11}	10^{7}
MPE_{DIR}, J-cm^{-2}	4.4×10^{-8}	1.6×10^{-6}
r_{NHZ} ($\rho = 1, \theta_v = 0$), m	850	1.2×10^{-2}
PEER, km	9×10^{6}	17.15
Energy density of beam, mJ-cm^{-2}	1.27	47.8

words, if an individual were standing next to the laser and looking along the direction of the beam and a 100-percent-diffuse-reflective Lambertian surface wall floated perpendicularly through the beam, then the individual would not receive the MPE_{DIFF} if the wall were more than 850 m from the laser's aperture.

This distance at first appears to be extremely low, especially when it is compared with the distance at which the beam is considered safe for direct ocular viewing with an unaided eye. However, in diffuse reflections, a collimated beam—a major characteristic that makes laser light so hazardous—has been removed. A Lambertian surface distributes the beam over 2π sr. Even though this distribution is not linear, but a cosine distribution, the hazard is greatly reduced. To give the reader a better understanding of the parameters and hazards for SELENE, table 2 contains a comparison of SELENE and a typical laboratory pulsed system.

As shown in table 3, of the 10 genera of clouds, 5 have lower surfaces that can form from ground level to 2 km (ref. 5). In terms of height, low-forming clouds have the potential to present a diffuse reflection hazard. The question now becomes, How reflective are clouds?

A comprehensive experimental study was performed by G. L. Stephens, G. W. Paltridge, and C. M. R. Platt on the solar and infrared radiation fields, liquid water content, drop-size distributions, and temperature and humidity profiles of six studies of uniform planetary boundary-layer clouds (ref. 6). The experimental results compared favorably with the theoretical calculations. Experimentally measured cloud albedos (or reflectivities) ranged from 0.488 to 0.746 for wavelengths between 8 to 13 μm.

For the highest cloud albedo, the minimum safe-viewing distance for a diffuse reflection from SELENE is 722 m. This value precludes any hot spots (areas of concentrated energy) in the original beam. If the original beam contains hot spots, then the minimum safe-viewing distance for diffuse reflection is greater than 722 m. A beam profile of SELENE needs to be performed to locate any hot spots, and these values need to be used to recalculate r_{NHZ}.

It is unlikely that SELENE would be operated in fog because the desired operating locations are arid desert sites; however, the hazards should be assessed for foggy conditions. As the beam passes through the atmosphere, it is absorbed and scattered by molecules (NO_2, SO_2, CO_2) and by particles (water droplets and dust). On clear days, most of the beam is transmitted through the atmosphere. (The attenuation coefficient μ for good visibility is 10^{-7} cm^{-1}.) Under heavy fog conditions, a significant portion of the beam is scattered back to the operator and can pose eye and skin hazards.

For heavy fog, μ is 10^{-4} cm^{-1}. When this value is included in the radiant exposure equation from reference 4, the reflected energy is determined by the following equation:

$$H = H_o \exp^{(-\mu r)} \tag{4}$$

If the fog bank extends from ground level to an altitude of 500 m, the range used for the laser beam is 500 m. The results from equation (4) indicate that the beam is reduced by more than 99 percent. (See

Table 3. Average Height of Clouds

[Data from ref. 5]

Type	Genera	Average height in—	
		Mid-latitude regions	Tropical regions
High cloud	Cirrus Cirrocumulus Cirrostratus	5 13 km	6 18 km
Medium (middle) cloud	Altocumulus Altostratus	2 7 km	2 8 km
Low cloud	Stratocumulus Stratus Nimbostratus	Surface to 2 km	Surface to 2 km
Clouds of great vertical range	Cumulus Cumulonimbus	500 m to cirrus level	500 m to cirrus level

fig. 1.) Some beam is absorbed, and part is scattered back to the operator. Depending on the density of the fog and the depth of the fog bank, 4 to 20 percent of the beam can be absorbed. Again, with the worst-case scenario, more than 95 percent of the beam can be reflected back to the laser operators; however, a more realistic scenario is portrayed in the example of diffuse reflections for ice clouds. The reflected beam under these conditions would be extremely hazardous to laser operators and any ground observers.

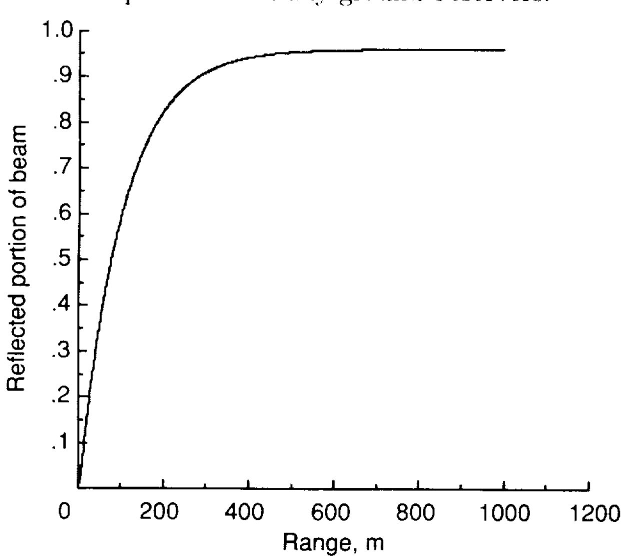

Figure 1. Range of laser beam (or altitude) versus portion of beam that is reflected and scattered for heavy fog conditions.

As shown in the previous fog example, SELENE should not be operated in some weather conditions. Safe operational procedures and shutdown procedures (if necessary) should be established for all weather conditions, including overcast and hazy conditions. Examples of atmospheric effects on the beam are shown in figures 2 and 3. Figure 2 shows the portion of the laser beam reflected and scattered for various visibilities for a laser beam transmitted through 500 m of atmosphere. Even during good visibility at this low altitude, 4 percent of the beam is lost through absorption and scattering. To emphasize the loss of the beam during good visibility, the loss of the beam is plotted against the range of the laser in figure 3. Continuous attenuation and no atmospheric turbulence was assumed for ease of calculation; however, turbulence and changes in attenuation may result in additional losses.

The r_{NHZ} for viewing a diffuse reflection of the laser beam is slightly greater for ice clouds than water clouds because the reflectivity is higher for ice clouds than water clouds ($\rho_\lambda = 1.0$ for ice clouds at $\lambda = 0.7$ μm, whereas $\rho_\lambda = 0.488$ to 0.746 at $\lambda = 8$ to 13 μm for water clouds (ref. 6)). Given the worst-case scenario, the minimum safe-viewing distance for a diffuse reflection off an ice cloud is slightly higher than for a water cloud: 850 m, which is calculated from equation (3). This value is the same as the worst-case scenario presented previously.

The probability of specular reflections from ice crystals (probability calculations were not performed for this paper) would be low because of the size and spacing of ice crystals in cirrus clouds. Ice crystals in cirrus clouds are predominately nonspherical hexagonal columns that are randomly oriented in

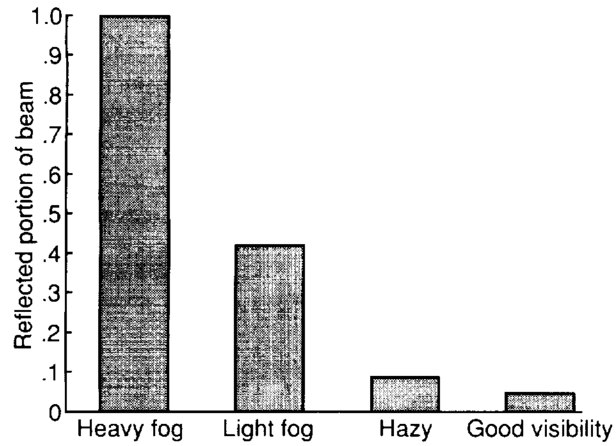

Figure 2. Reflected portion of laser beam at a range of 500 m for atmospheric conditions ranging from heavy fog to good visibility.

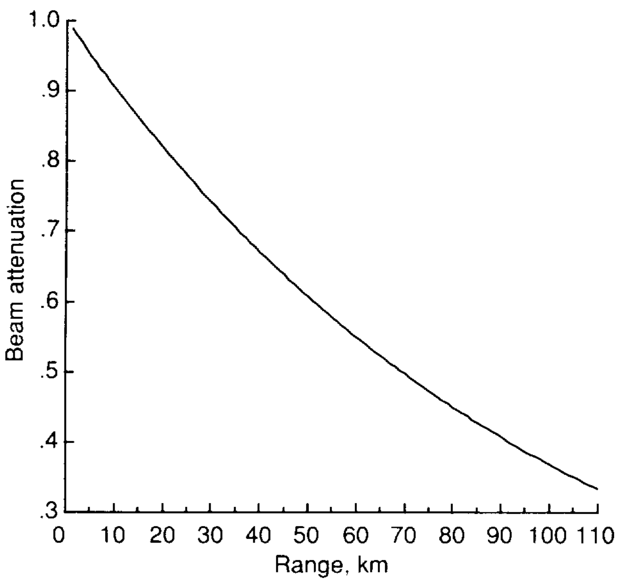

Figure 3. Beam attenuation versus range of laser for a clear day ($\mu = 10^{-7}$ cm^{-1}).

space, about 200 μm long and 30 μm wide, and the average particle concentration is $\approx$0.5 cm^{-3}. (See ref. 7.) However, should a specular reflection occur from an array of ice crystals that is larger than the diameter of the pupil of the eye (7 mm), the exposure would be greater than the MPE for eyes and could result in possible eye injury.

The previous examples treat clouds as solid, diffuse reflecting surfaces. A more accurate description of the reflection processes in clouds is to consider the interaction of the laser beam with individual particles of ice and water. Clouds are composed of billions of water and ice particles. The reflectivity and absorption properties of individual crystals vary greatly; the numerous absorption and transmission events of the beam by these particles would attenuate the intensity of the beam. (See fig. 4.) In many cases, the scattering and scintillations occurring could annihilate the reflected beam before it is reemitted from the cloud formation. If the beam does reemit from the cloud, then factoring in the atmospheric attenuation could tremendously reduce the intensity of the beam. For example, on a clear day the initial beam irradiance would be reduced to 1.06×10^{-3} J/cm^2 after traveling a range of 18 km. On a hazy day with an attenuation of 1×10^{-5} cm^{-1}, the intensity of the beam would drop to 1.8×10^{-11} J/cm^2 (three orders of magnitude less than the MPE for eyes) after traveling the same range.

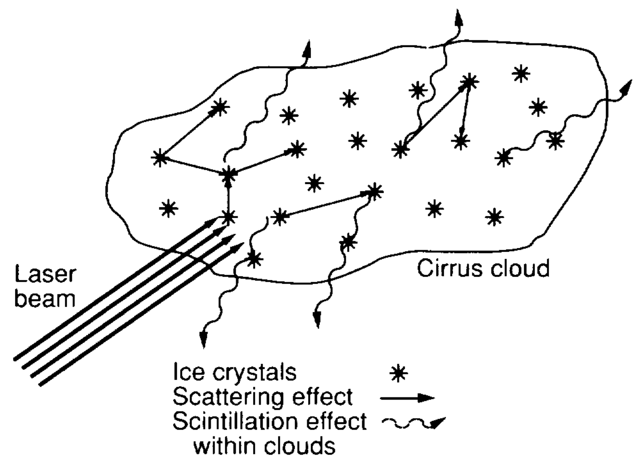

Figure 4. Effect of laser beam passing through cirrus clouds.

This paper addresses the hazard to the laser operators and ground observers; however, another group that needs to be considered is aircraft personnel and passengers. The use of air space for SELENE, as with aircraft, falls under the Federal Aviation Association; whose notification is necessary before any laser can be used in the atmosphere; with a laser as powerful as SELENE, special approvals and safety precautions may be needed.

To eliminate any question of potential hazards from cloud reflections, reflection experiments should be performed at each SELENE site and will probably be required by the organizational safety office before operation. These measurements can be made by using a much less powerful free-electron laser before the construction of each SELENE base and for a reasonable funding outlay. The major expenses are a free-electron laser, several detectors, technicians, and travel expenses.

Concluding Remarks

For high-forming and middle-level clouds, diffuse reflections from Segmented Efficient Laser Emission for Non-Nuclear Electricity (SELENE) off cloud surfaces should offer minimal risk to ground observers. Low-forming clouds (cumulus and cumulonimbus clouds) could present significant diffuse hazards if formed less than 750 m to the Earth's surface. In addition, diffuse reflections from fog and any specular reflection from SELENE would present a significant hazard to laser operators and any ground observers. Regulations need to be established from experimental data and the American National Standards for the safe operation of SELENE for cloud, fog, and various atmospheric conditions. Additional modeling and testing must be performed and Federal Aviation Association approval must be obtained before implementation of SELENE.

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